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# NASA Facts

An Educational Publication  
of the  
National Aeronautics and  
Space Administration

NF-117/8-81

(NASA-Facts-117/8-81) MATERIALS AND  
STRUCTURES/ACEE (National Aeronautics and  
Space Administration) 8 p HC A02/MF A01

CSSL 01C

N82-25242

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## Materials and Structures/ACEE

Weight reduction is a goal of every aircraft design. Unnecessary weight translates into additional fuel burned. To develop an energy-efficient aircraft, thorough and painstaking analysis must be applied to the design of the airframe, to make it as light as possible consistent with the requirements of flight safety.

Contemporary aircraft are constructed almost universally from metal alloys, primarily aluminum. But a new family of construction materials called composites, made from fibers of graphite, glass, or man-made materials held in an epoxy matrix, offer the possibility of fabricating very light structures that are simultaneously very strong and stiff.

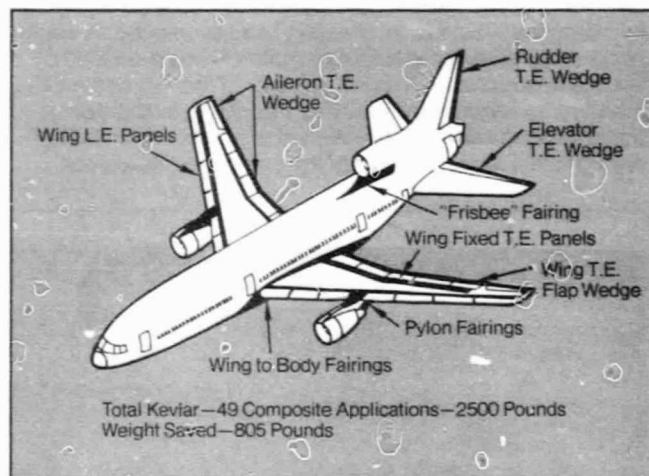
The investigation of those composite materials and of their application to a wide variety of typical air transport structural components is one of the six phases of the Aircraft Energy Efficiency (ACEE) program managed by the National Aeronautics and Space Administration.

The basic goal of the ACEE program is to develop aircraft technologies that use fuel energy more efficiently. That, in turn, will reduce the factor of energy cost in flight operations by the commercial airlines, the military, and eventually by general aviation.

ACEE is a planned, ten-year program that was first developed in response to a request from the United States Senate Committee on Aeronautical and Space Sciences. It looks simultaneously at both the near-term and the far-term problems. It attempts to develop expedient solutions that can be applied first to current aircraft and engines, then to their derivatives that can be expected to arrive in a few years, and ultimately to wholly new classes of transports and propulsion systems designed specifically to be fuel-efficient.

The workload of the ACEE program is divided among several NASA research centers. Langley Research Center, Hampton, Virginia, is responsible for technology studies in aerodynamics, and in materials and structures. The wind-tunnel testing is shared by Langley and the Ames Research Center, Moffett Field, California. Flight experiments are conducted by the Dryden Flight Research Center, Edwards, California. Propulsion research is done at the Lewis Research Center, along with some technology development on materials and structures, particularly as they pertain to powerplant applications.

NASA is joined by other organizations in this work. The airlines, final users of the product, have furnished valuable input through contracted studies of their real-



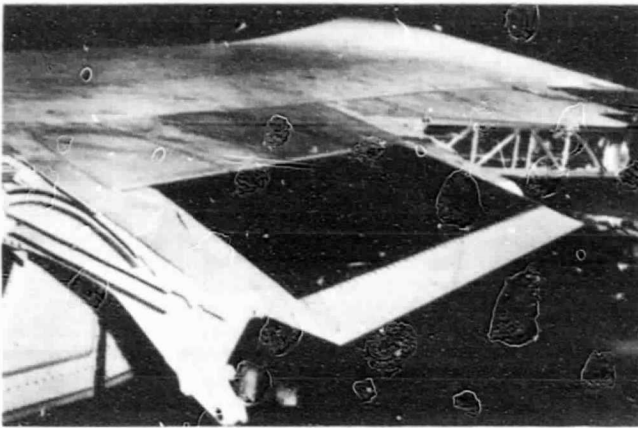
**Figure 1:** Typical use of composite materials in the fabrication of aircraft parts is shown on this sketch of the Lockheed L-1011-500. Fairings, panels and control surface components have been fabricated from Kevlar-49 epoxy laminate. Experience gained during a joint NASA/Lockheed program on Kevlar-49 wing-body and center engine fairings was a major contributor to these extended applications of composite material. More than seven years of use on Lockheed L-1011 transports has confirmed the durability of the materials in airline service.

world operations. Airframe and engine manufacturers, possessing their own research facilities as well as full-scale aircraft and engines to test, also are a part of the ACEE team.

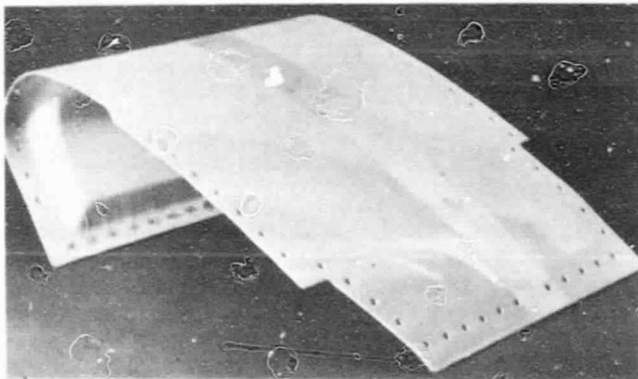
Overall, the broad purpose of the program is to provide an inventory of technology that can be used by the major manufacturers of transport aircraft and engines in the United States. It will help them to develop near-term derivative airliners that extend their current product lines; it will assist in the design of families of new aircraft for the near term; and it may direct thinking toward some radically different, new form of transport aircraft for the far term.

### Historical Background

NASA work with composite materials predates the Aircraft Energy Efficient program. The initial spur was a meeting of industry, university and government repre-



**Figure 2:** This aileron for the Lockheed L-1011 was developed as part of the NASA program for energy-efficient aircraft. It is located inboard on the wing and measures approximately 92 by 50 inches in plan form. Designed and developed by Lockheed under contract to NASA, the aileron was produced by Avco Aerostructures Division. Ten sets of the ailerons will be installed on commercial L-1011 transports in airline operations, for an in-service evaluation of the durability and other performance characteristics of the composite structures.



**Figure 3:** Kevlar-49 epoxy is formed into a wing leading-edge panel for the Lockheed L-1011, using honeycomb sandwich construction to give depth and stiffness to the piece. The smooth surface finish is one of the desirable characteristics of composite structures.

sentatives early in 1972. Their goal was to develop a long-range planning study for the eventual use of composite materials in both NASA and U.S. Air Force applications.

Under the overall project designation of RECAST, the joint study cited the two major stumbling blocks in the way of increased use of composite materials. The first was what was then the lack of confidence in the materials. There had been no earlier applications of composites on a scale large enough to obtain any realistic production cost data, or service life information, or to answer many of the questions relating to the long-term properties of structures built wholly or in part from composites.

The second hurdle was cost. That, of course, is a problem common to the introduction of almost any new material. Initial costs are high because there is no volume production of the material demanded by its

widespread application. There is no widespread application because the cost is high. Finally, some enterprising manufacturer breaks the vicious circle, and costs begin to go down.

The joint study approached these two barriers with a series of recommendations. First, to build confidence, it suggested that some programs be established to fabricate and test composite components under realistic service conditions. Second, it encouraged the application of composites to new designs. Third, it recommended a program of in-depth studies that would develop the technology and would provide a data base for designers.

On the question of cost, the study acknowledged that it was closely related to volume, but that improved structural concepts, improved design procedures, and innovations in materials and fabrication techniques should result in some major cost reductions.

NASA's program grew out of RECAST; it focused on building confidence in the composites, with cost as an important secondary consideration. Because the only way to get service life experience is to build some useful components and test them, NASA also focused on specific applications of composites to existing vehicles such as spacecraft, powerplants and transport aircraft. Although aimed directly at one or more of these specific uses, the application of composite materials was expected to produce data that would be of a much more general nature for the widest variety of vehicles and engines.

As it happened, the work planned for application to transport aircraft would later contribute greatly to the work with composite materials that was to be organized under the ACEE program.

## Composite Characteristic

What we think of currently as conventional aircraft structures are pieces made from alloys of aluminum, magnesium, titanium, and steel, with a very small percentage of those pieces made from plastics.

Composites are unconventional. They consist of filaments—long fibers—of graphite, glass, or Kevlar® which are arranged in a matrix to hold them. That matrix generally is an epoxy, although it may also be other plastics or metals.

The filament materials can develop very high strength, approaching that of pure crystals of the material. By proper arrangement in the matrix, that strength can be concentrated along a line, in a uni-directional composite, or in random directions.

The composites are light, yet strong and stiff. Their very high strength-to-weight and stiffness-to-weight ratios make them candidate materials for weight savings in new design approaches. And those weight savings can be substantial, typically being 25 percent or more, depending on the particular application.

The weight reduction comes from the strength-weight and stiffness-weight characteristics of the material. Potential cost reduction comes from the fact that a



**Figure 4:** The simplicity of the fabrication of composite structures is typified here by this test piece under construction in Lockheed's tape layup room. Left in the picture is a finished specimen; on the right, two workers are completing the layup of material sheets before sending the piece to an autoclave for curing.

fewer number of pieces make up a composite assembly, compared to conventional metal structures. And a further cost saving comes from the fewer number of fasteners required in the fabrication.

A typical design application of a composite material takes full advantage of its special characteristics. Contemporary graphite epoxy composites available from commercial sources show ultimate strength and stiffness as high as steel but at one-fourth the weight. In addition, the fiber can be oriented in the desired direction to provide tailored stiffness properties. Modern composite tennis rackets are an excellent example of this tailoring, providing the best combination of bending and torsional stiffness.

Composites can easily be fabricated, using a hand lay-up technique familiar to anyone who has ever built a fiberglass boat hull or car body. The skill can be learned in a fraction of the time it takes to acquire competence in sheet-metal fabrication. Currently, automated cutting and lay-up techniques are being developed to reduce costs further.

These new materials have outstandingly good fatigue characteristics. Graphite-epoxy exhibits twice the fa-

tigue strength of aluminium. In the presence of stress concentrations such as holes or cracks, the composite is even more resistant to fatigue loading, and cracks propagate more slowly. As a result, fatigue, which traditionally is a limiting factor for metal aircraft structures, has become a secondary factor for composites. Many composite aircraft structures exhibit unlimited life characteristics.

One of the most important properties of composites is their resistance to corrosion, an enemy to any aircraft built of metal alloys. Possible sources of corrosion are everywhere: At fasteners, where they pierce successive layers of different metals; or inside the fuel tanks, where strains of bacteria thrive on metal spars. But composites, being non-metallic, are immune to corrosion.

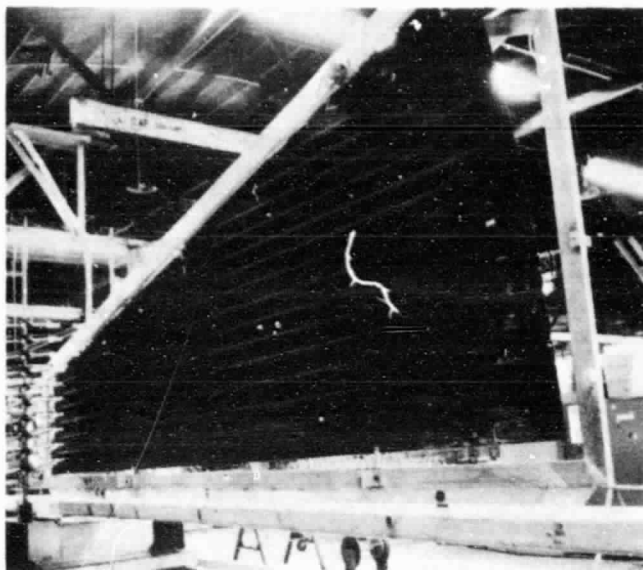
It's interesting to note that the materials themselves are energy-efficient. It is well-known that it takes a large amount of electrical energy to produce aluminum for industry. But an equal amount by weight of composite materials takes only one-eleventh of the total energy required to produce aluminum. Even steel, which compared to aluminum requires a relatively low energy level for production, takes four times as much energy per unit of weight produced as the typical composite material.



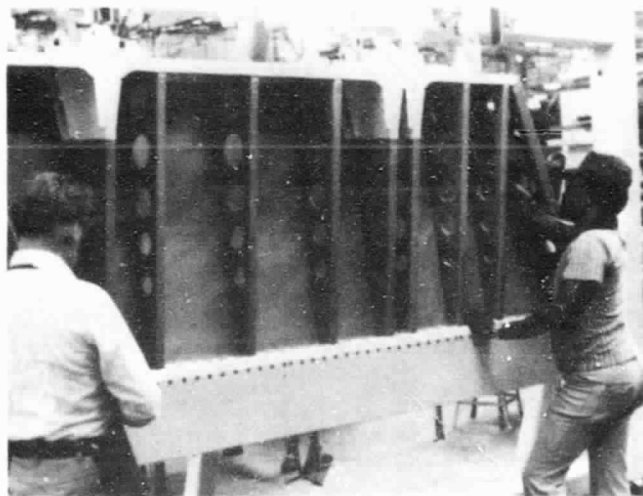


**Figure 5:** Continuing evidence of the value of composite materials in fabrication is shown in the increasing use in the construction of parts for commercial air transports. These engine cowl doors on the Lockheed L-1011-500 were designed and developed by Rolls-Royce, manufacturer of the plane's engines, and were built by British Aerospace. Construction is a sandwich of aluminum honeycomb with a graphite/epoxy face sheet. Weight saving is about 70 pounds per door, compared to conventional methods of construction using metal alloys.

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**Figure 6:** The vertical stabilizer central box structure for the Lockheed L-1011 transport has been redesigned and fabricated from composite materials as part of the NASA Aircraft Energy Efficiency program (ACEE). The composite unit is 25 feet high and has a nine-foot chord at the root. The piece shown here is a skin cover, stiffened by hat sections. It is positioned for an ultrasonic inspection to check the integrity of the fabricated piece.



**Figure 7:** A weight saving of 26 percent has been achieved in the construction of this Lockheed L-1011 aileron by using composite materials. And, because the number of parts has been substantially reduced, the manufacturing costs are expected to be comparable to those associated with conventional metal alloy structures. A thin sandwich cover skin, formed of graphite/epoxy tape and a syntactic core of epoxy, has such inherent stiffness that the number of bracing ribs was reduced from 18 to 10. Ribs and spars themselves are simple channel sections, easily laid up in composites.

## Acceptable Risks

One potential problem that has been identified with graphite epoxy composites, stems from the fact that graphite fibers are excellent conductors of electricity. There has been a fear that a fire, burning an airplane

that contained some of these composite structures, could consume the epoxy matrix. A cloud of tiny fibers could be broadcast downwind, where they would raise havoc with power substations, transformers on poles, and perhaps even on home appliances.

For a while, NASA slowed its work on composite structures in airline service while evaluating the actual magnitude of the risk, and the possibility of its occurrence. The studies showed that there was, in fact, a definable but insignificant risk. The yearly loss by the early 1990s due to accidental release of graphite fibers from transport aircraft is estimated at \$1,000. There is only one chance in 2,000 of the total loss for the year exceeding \$150,000.

## Building Parts and Confidence

NASA's first step in the program to build industry confidence in the composite materials was to plan for the development, fabrication and testing of a number of components of aircraft secondary structures, those parts of an airframe that are lightly loaded and are not critical to the safety of flight should they fail. Examples of those parts are access doors, fairings, or sections of multiple and redundant control surfaces.

Specifically, NASA then contracted for the design and fabrication of sets of wing spoilers for the Boeing 737, some external fairing panels for the Lockheed L-1011, and the upper segment of the split rudder on the McDonnell Douglas DC-10. The primary purpose of the study was not to save weight; that was a known fact about composite structures. Besides, the parts chosen were relatively so small that—had they weighed nothing at all—the overall weight reduction for the airplane would have been negligible. The real goal of the study was to get some composite components into daily use in the active environment of a commercial airline, where rain and snow, ice and hail, dust and dirt would add to the routine wear-and-tear on the pieces.

For the ACEE program, the NASA plan called for a phased development leading by steps to the design, fabrication and testing of a complete wing and fuselage which would be typical of the type around which a future energy-efficient transport might be built. The first phase of the program was a series of contracts for representative secondary structures: Elevators for the Boeing 727, ailerons for the Lockheed L-1011, and rudders for the McDonnell Douglas DC-10.

Those were followed by contracts for medium-sized primary structure in the second phase of the program: The entire horizontal tail for the Boeing 737, and vertical fins for both the L-1011 and the DC-10. In the final phase—the development of the wing and fuselage—everything learned from the first two phases would be poured into the work.

Because these components were to replace equivalent metal structures on passenger-carrying aircraft in airline service, each part had to be certificated to the requirements of the U.S. Federal Aviation Administration. The timetable called for all of the first-phase components to be in airline service by 1981, and the first two medium-sized primary structure pieces to be

test-flown by 1981. Verification of all the test data and establishment of service life characteristics was scheduled to take five years.

These composite structures are being fabricated with production-quality tooling. In addition to the components built for in-service testing, at least one set of each part will be constructed for ground testing. To meet the FAA requirements for certification, one example of each flight-worthy component also must undergo ground vibration, in-flight flutter, and stability and control tests.

A sufficient quantity of each will be built to establish a learning curve so that valid estimates of manufacturing costs can be made. Ten sets of ailerons and three vertical fins are in the Lockheed L-1011 program. Boeing will build five complete horizontal stabilizers for the 737, and McDonnell Douglas will fabricate six DC-10 vertical fins.

The parts in airline service will be treated exactly like the metal components they replace, receiving the same sort of periodic inspection and maintenance.

It should be emphasized that these test sections are not small surfaces, although their descriptions may lead one to think so. The upper rudder segment for the DC-10 is 12 feet long. Certificated in May 1976, it has been in airline service since then. Its weight saving was about 30 percent compared to the weight of the conventional metal rudder segment it replaced.

The L-1011 vertical fin measures about nine by 25 feet, and saved about 25 percent in weight in the composite design compared to the original metal structure.

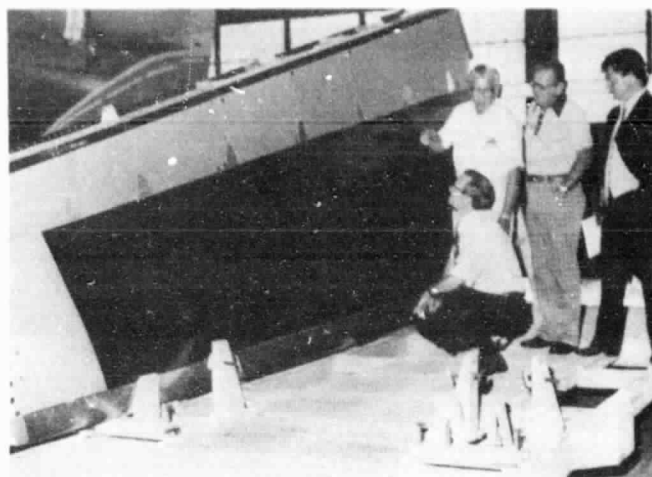
Boeing, in its design of the B-727 elevators, found that the number of ribs required was reduced from 27 in the metal piece to 14 in the composite lay-up. The number of fasteners was reduced dramatically, by 60 to 70 percent. This particular piece still retains some aluminum alloy pieces, but the weight saving still is about 30 percent, and the required mass balance weight has been halved.

With these two design and fabrication phases under way, studies of the complete wing layout were undertaken by each of the three major manufacturers of U.S. transport aircraft, working toward the selection of a final configuration for detailed design and full development. The wing and fuselage development is scheduled to begin in the early 1980s and be completed through ground testing by the mid-1980s.

## Aeroelastic Tailoring

The current emphasis on high aspect ratio wings for future transport design has brought with it some structural problems as the price for high aerodynamic efficiency. They revolve around the aeroelastic characteristics of such a wing. Because of its large span, relatively narrow chord, and the sweepback angle, the wing is inherently susceptible to air loads that could make it respond erratically in flight, perhaps dangerously.

Active control systems offer one way of easing the aeroelastic response of the new wing planforms. (See NF-95, "Guidance and Control/ACEE", for a more detailed discussion of active control systems and their

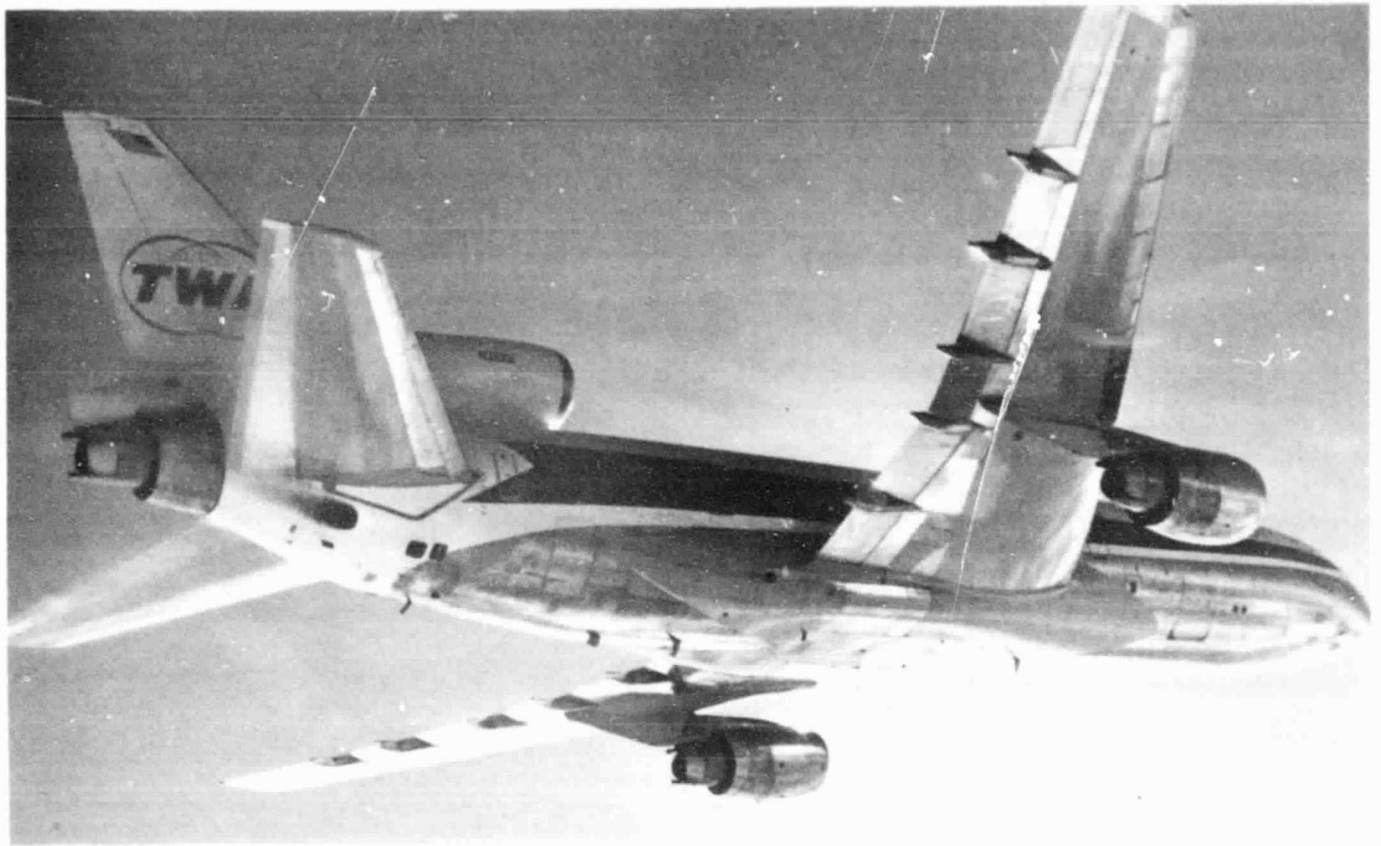


**Figure 8:** A major change in any structural or other vital component of an aircraft requires a recertification to requirements established by the Federal Aviation Administration. The Boeing 737 horizontal stabilizer, fabricated from composite materials under the NASA ACEE program, is such a case. This ground test specimen will be thoroughly evaluated under loading conditions that simulate operational use before the airplane will be cleared for flight with the new surfaces.



**Figure 9:** This upper rudder segment of the McDonnell Douglas DC-10 transport was one of the first composite components built under the ACEE program. It was chosen to evaluate composite structure in daily airline use, where it would be subjected to all the environmental factors of those operations. In that way, industry confidence in the new materials could be built, and later applications could extend the use of the new materials to more advanced and larger structural components.





**Figure 10:** The rust-colored area on the right wing of this Lockheed L-1011 transport is the inboard aileron, fabricated from advanced composite materials. It is one of ten sets that have been installed on commercial transports in order to gather operational data on the durability and serviceability of the new composites.



**Figure 11:** This in-flight photo of the Lockheed L-1011 prototype transport has been retouched to show the outline of the vertical stabilizer box structure being fabricated from composites. The outlined section is the central component of the fin to which leading-edge assemblies and trailing-edge control surfaces are attached. The box structure is about 25 feet tall.

application to current and future aircraft designs for energy efficiency.)

But passive control methods, using a new approach to the structural design of the wing, offer great promise. The passive method is based on the aeroelastic tailoring of the wing, designing and fabricating into it the needed stiffness in critical areas to produce the re-

quired dynamic response where it is desired. This is a far easier procedure to achieve with a composite structure than with conventional ones.

NASA has begun a program that will design, fabricate, and test a wing with aeroelastic tailoring. It will be built in a size that is large enough to give a good approximation of full-scale data, yet small enough to be tested in NASA wind tunnels and in flight on a small drone aircraft.

Composite structural materials also are contributing to the evolution of a laminar-flow control (LFC) system for advanced transports. Part of the LFC studies, one of the sub-programs under the overall ACEE mantle, is concerned with new kinds of structural designs which are needed to make the laminar-flow system a reality.

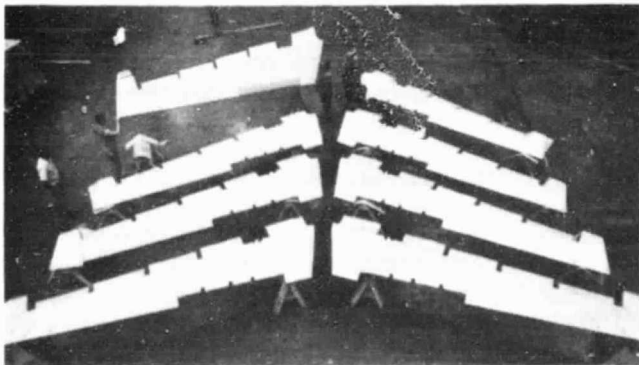
The structural requirements for a typical LFC wing, as currently visualized, call for a very efficient, light and stiff structure capable of providing a large internal volume for the removal and handling of the boundary-layer air. Composites are obvious candidate materials for such a wing design, and in fact are being considered for that purpose.

One example: A glove structure was conceived as a way of modifying an existing wing for early tests of a section of a representative LFC system. The glove included an inner structure built of blade-stiffened composites. The blades provided a set of boundaries for the internal ducting used to handle the boundary-layer air.





**Figure 12:** The elevators on this Boeing 727 for United Air Lines look like any other elevators for that long-lived transport. Developed under NASA's ACEE program, they are made of composite materials instead of the traditional aluminum alloys. Five Ship-sets (left and right side) are installed on commercial airliners for an inservice evaluation of the new structural materials. The first set was flown by Boeing on one of its own flight test 727 aircraft, and logged more than 500 operational hours, trouble-free. Boeing plans to use composite materials for control surfaces on its new commercial transports, the 757 and 767.



**Figure 13:** Four sets of composite elevators for the Boeing 727 transport are shown before installation at the company's plant. The control surfaces were built as part of the ACEE program to investigate the performance of components made from composite materials in the day-to-day environment of airline operations. These elevators have been installed on Boeing 727s bought by United Air Lines, and will be evaluated periodically in regular airline service.

A second example visualized a slotted titanium surface bonded to a stiffened composite structure to carry the primary loads imposed on the wing. Stiffeners in the composite piece form the side walls of the air ducting.

These programs, all aimed at future use in air transportation, are one part of a national effort to encourage the further development and use of composite materials. NASA is not alone in this field; other work is being done under contract to the U.S. Air Force, Navy, and Army. Major military aircraft components have been designed and fabricated, and are being introduced into service. Both the Northrop F-18 and the McDonnell Douglas AV-8B have composite wings.

Private industry has been conducting its own studies on varying scales, and significant numbers of composite components now are being built for production aircraft.

NASA's contribution is to give direction and impetus to the program, to seek out new ways to investigate all the characteristics of the new materials, and to develop components that can be monitored over their life cycles to obtain service data. The resulting data bank will become a major national resource, available to the designers of future aircraft.

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